INTERGRATING AMPLIFIER FOR X5A COMPUTER

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INTRODUCTION

The following reports represent the results of the three months term spent at Westinghouse Electric Corporation, Baltimore, Maryland, and are submitted as the required term report. Since these reports were written also for Westinghouse, they are shorter and less detailed than if they had been written exclusively as a term report. For example: the report on the integrating amplifier mentions that a "suitable operational amplifier was available" -- at the beginning of the term, this amplifier was still being built. The labor and time involved in calculating its characteristics and then measuring them to see if it was suitable was not mentioned; it has been covered in another Westinghouse report. Extra graphs, therefore, have been included for the sake of completeness, but naturally they are not referred to in the text.

CONCLUSIONS

1. The third term field trip is essential. It enables a Naval officer to understand the problems of design and allows a student to solidify his past learning.

2. The curricula should include more material on operational, or feedback, amplifiers. Their importance is shown by the fact that when the frequency, gain, and/or distortion characteristics of an amplifier are specified, then feedback must be used. Although the topic of feedback was discussed in the electronics course, and amplifiers touched upon in the advanced circuit analysis course, the full capabilities of operational amplifiers were not brought out. Since LaPlace transforms greatly simplify their analysis, some time could be devoted to them either in the advanced circuit analysis course, or in the servo mechanisms course.

NO. AA-14

DATE 3-17-52

WESTINGHOUSE ELECTRIC CORPORATION

AIR - ARM DIVISION

FRIENDSHIP INTERNATIONAL AIRPORT, BALTIMORE, MARYLAND

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SYNOPSIS

This report will cover the design and testing of an integrating amplifier, and its associated demodulator, used in the X5A computer to measure the change in dive angle.

STATEMENT OF PROBLEM

1) To construct an integrating amplifier with the following characteristics:

   a) Output to be linear within ±5% for a five second interval.

   b) Zero signal output voltage (d-c drift) not greater than 50 millivolts, but preferably less than 30 millivolts.

   c) To have an output voltage of approximately 60 volts at 5 seconds after a step input voltage of 44* volts is applied.

2) To construct a demodulator for use with the integrating amplifier.

CONCLUSIONS

Demodulator

1) For inputs of .2 volts or more, linear rectification was obtained.

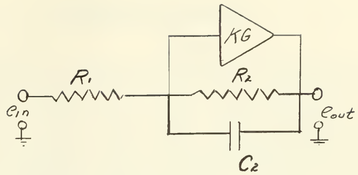
2) Zero output voltage was obtained for a zero voltage input.

3) The maximum error occurred at an input voltage of .2 volts; from that point the error continuously decreased until it became negligible at an input voltage of 6.5 volts.

Integrating Amplifier

1) The integrating amplifier with the required characteristics should consist of the operational amplifier, mentioned in report AA4 with the following feedback network:

*This figure was raised to 48 volts before this went to press.



2) The network component values are:

R_1 = 3M - - 1/4% tolerance

R_2 = 30M - - 5% carbon resistor

C_2 = 1 mfd - - as high a precision as obtainable

3) The transient solution and the log modulus vs phase angle plot show that the integrator is extremely stable with no transient effects, and that the transfer function is determined by the feedback network alone. Serious changes in operating conditions of tube characteristics, filament and supply voltages, and temperature have no measurable effect on the integrator.

4) The operational amplifier previously mentioned has been proven to be an extremely stable, high gain d-c amplifier which can be used in summing, differentiating, and integrating amplifiers.

BODY OF REPORT

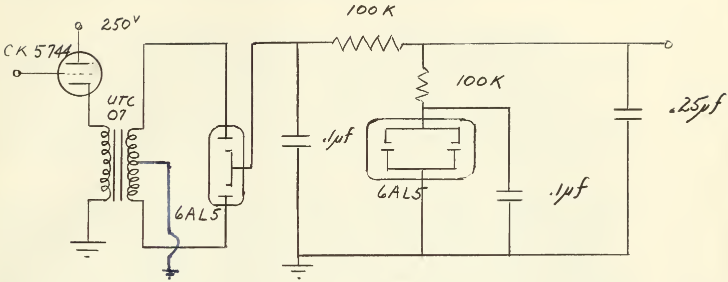
Demodulator

The demodulator was constructed in accordance with general theory[1].

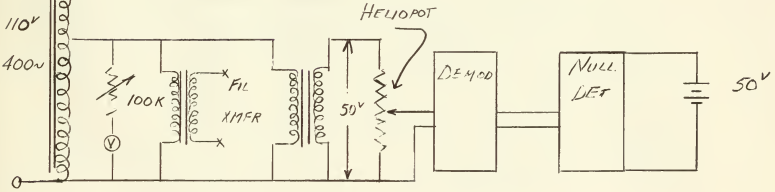
The second 6AL5 tube and filter was added to eliminate the zero signal output voltage by neutralizing the contact potential of the first tube. Ordinarily this contact potential of approximately .5 volts can be ignored, but with a d-c amplifier following this stage, that residual voltage must be eliminated. The addition of the extra diode also halved the original output.

Note: [1] Radio Engineers Handbook: F.E. Terman.

DEMODULATOR SCHEMATIC



MEASURING CIRCUIT FOR THE DEMODULATOR CHARACTERISTICS



After the variac was adjusted for 6.3 volts across the filament transformer, the rheostat was adjusted to give full deflection on the fifty volt scale. Any change in the line voltage could now be detected

and corrected, thus insuring a constant heater voltage. (The plate supply voltages were obtained from regulated power supplies).

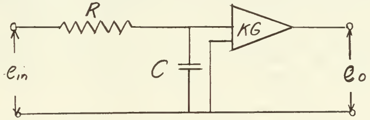
The null detector consisted of a sensitive galvanometer connected in series with the input terminal and a duodial heliopot shunted by a known voltage source. The unknown voltage input is balanced out by feeding in a known voltage via the heliopot. The galvanometer detects the balance or null point. A duodial helipot is also used to feed various input voltages (up to 50 v) to the demodulator. Since the two heliopots are linear to .05%, the dial readings can be plotted instead of converting them to actual voltages, and then plotting the voltages.

The theoretical rectification curve would be a straight line, but the expected curve will have a "toe" at the origin.[1] Using 50 volts across the input heliopot, a plot of output versus input scale readings was made. This showed the expected linear rectification curve with the "toe" near the origin. To check the region of the "toe" more closely, the area was expanded by putting 10 volts across the heliopots, and using the same scale range for another plot. This one showed that the rectification was linear with negligible error at 6.5 volts and a maximum error of .2 volts occurring at the origin. (See figure 1 in the appendix.)

Integrating Amplifier

For a perfect integrator,[2] $\frac{E_{out}}{E_{in}} = \frac{1}{s}$. The problem was to obtain a system whose transfer function approached the ideal. Several solutions were considered:

1) An R-C integral network followed by an amplifier.

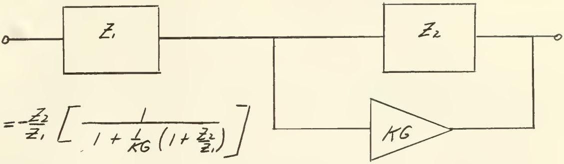


$$e_o = (KG)e_{in}\left(1-\epsilon^{-\frac{t}{RC}}\right)$$

Note: [1]Radio Engineers Handbook: F.E. Terman

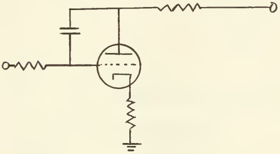
[2]Transients in Linear Systems, vol. 1: Gardner and Barnes

2) An operational amplifier with an integrating network.



$$\frac{e_o}{e_{in}} = -\frac{Z_2}{Z_1}\left[\frac{1}{1+\frac{1}{KG}\left(1+\frac{Z_2}{Z_1}\right)}\right]$$

3) A "capacitor amplifier" using the "Miller Effect"

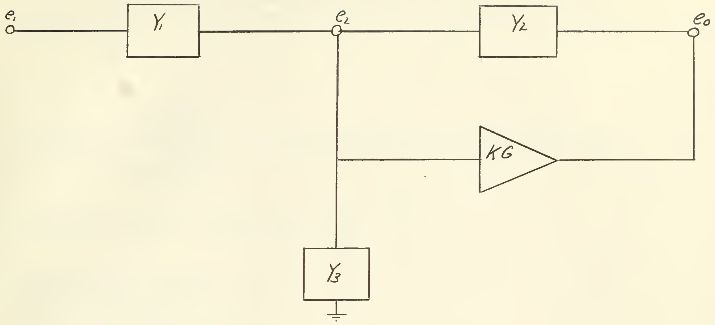


4) Phantastron or a bootstrap linear sawtooth generator.

The drift problem associated with pure capacitive feedback precluded the use of the capacitor amplifier. Since an excellent operational amplifier[3] was already in the computer, the sawtooth generator was discarded. Use of the R-C integral network followed by the amplifier necessitated the use of large, high precision components, and constant amplifier gain, whereas the operational amplifier required only two precision components, and its performance was almost independent of the amplifier gain; it was, therefore, the logical choice.

With the choice of the operational amplifier, the problem had been resolved to the design of the R-C network. Obtaining the transfer function in general terms:

Note: [3] AA4 Report: by C. Glover



KG is the transfer function of the amplifier.

Using LaPlace transforms:

1) $E_o = (-KG)E_2$

2) $E_2\,(Y_1+Y_2+Y_3)-E_o(Y_2) = E_1Y_1$

$$\frac{E_o}{-KG}\,(Y_1+Y_2+Y_3)-E_oY_2 = E_1Y_1$$

$$\frac{E_o}{E_1} = \frac{-KGY_1}{Y_1+Y_2+Y_3+KG\,Y_2}$$

$$\frac{E_o}{E_1} = -\frac{\frac{Y_1}{Y_2}\;KG}{KG+\frac{Y_1+Y_2+Y_3}{Y_2}}$$

$$\frac{E_o}{E_1} = -\frac{Y_1}{Y_2}\left[\frac{KG\,\frac{Y_2}{Y_1+Y_2+Y_3}}{1+KG\,\frac{Y_2}{Y_1+Y_2+Y_3}}\right]$$

The equation in this form shows that, if the gain of the amplifier can be made high enough, the transfer function will depend only on $\frac{Y_1}{Y_2}$.

A plot of $\dfrac{KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}{1+KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}$ on a log modulus versus phase angle graph

shows the effects of finite gain on $\frac{E_o}{E_1}$.

Expanding into series:

Let $x = KG\dfrac{Y_2}{Y_1+Y_2+Y_3}$

$$\frac{E_o}{E_1} = -\frac{Y_1}{Y_2}\,\frac{x}{1+x} = -\frac{Y_1}{Y_2}\,\frac{1}{1+\frac{1}{x}}$$

Using Binomial Expansion Theorem:

$$\frac{1}{1+v} = 1-v+v^2-v^3 - - - - - - \text{ where } v = \frac{1}{x}$$

$$\frac{E_o}{E_1} = -\frac{Y_1}{Y_2}\left[1-\frac{Y_1+Y_2+Y_3}{KGY_2}+\left(\frac{Y_1+Y_2+Y_3}{KGY_2}\right)^2-\left(\frac{Y_1+Y_2+Y_3}{KGY_2}\right)^3+ - - - - -\right]$$

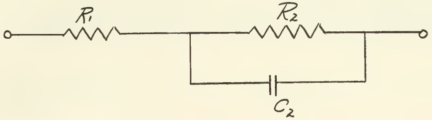
where $0 < \dfrac{Y_1+Y_2+Y_3}{KGY_2} < 1$

The preceding equation demonstrates more clearly that, if the gain of the amplifier is high enough, $\frac{E_o}{E_1} = -\frac{Y_1}{Y_2}$. As the gain of this amplifier[3] is greater than 1000, the transfer function may be assumed

Note: [3] AA4 Report by C. Glover

to be the ratio of feedback impedances. The feedback network was designed on that assumption, and the values obtained were checked with a complete transient solution and log modulus versus phase angle plot.

The initial solution gave the following:



$$\frac{E_o}{E_1} = \frac{G_1}{G_2+C_2 s} = \frac{1}{R_1C_2\left(s+\frac{1}{R_2C_2}\right)}$$

This equation shows:

1) The gain varies inversely as R_1C_2

2) The larger R_2C_2 becomes, the closer the perfect integrator is realized.

3) R_2 is not a critical component as long as R_2C_2 is large enough for the required linearity.

4) R_1 and C_2 are critical.

Since a high quality 3 Megohm resistor and 1 mfd capacitor were already present (and not in use at the same time as the integrator), those particular values were chosen for R_1 and C_2 respectively. Instead of using two sets of high precision components, one set was to be used in the computer for two different purposes by means of a switching arrangement, thereby saving space, weight, and money.

Because the linearity depended directly on the R_2C_2 product, a 50 Megohm carbon resistor was initially chosen as the highest practical resistance under the expected working conditions.

With the components values tentatively decided upon, the problem of testing and confirming them had to be solved next. From the requirements of the system[4], the severest task that the integrator had to

Note: [4] Functional Diagram of X5A

perform was to yield a linearly increasing voltage for a step input voltage 44 volts high.

Since 5% error limits are specified, the question arose of how to measure the error involved. With a step input voltage, the output should be a linearly rising voltage - - - actually it will be an exponential rise. The first possibility was to draw a tangent to the exponential at the origin, and use that as a criterion for error. Using Laplace transforms to obtain an analytical expression for the tangent:

For an input voltage

$$e_{in} = e_1\, u(t)$$

$$E_o = \left(\frac{E_1}{R_1C_2}\right)\frac{1}{s\left(s+\frac{1}{R_2C_2}\right)}$$

To find slope, differentiate:

$$\frac{de_o}{dt} = sE_o = \left(\frac{E_1}{R_1C_2}\right)\frac{1}{s+\frac{1}{R_2C_2}}$$

To find the value of the initial slope, use initial value theorem:

$$\left.\frac{de_o}{dt}\right|_{t\to o} = \lim_{s\to\infty}\frac{dE_o}{dt} = \frac{E_1}{R_1C_2}$$

$$\text{Initial slope} = \frac{E_1}{R_1C_2}$$

If $E_o = \dfrac{E_1}{R_1C_2}\, t$, a perfect integrator (step voltage input)

would be obtained. The initial slope, therefore, could be used as a criterion of the error. Hereafter, it will be called the "theoretical linear curve" (See appendix fig. 3).

Another basis for determining the error is to draw a straight line through the exponential curve to give equal areas of error above and below the straight line (See appendix fig. 2).

If the first method is chosen, the error varies directly with time: being negligible at first, and becoming greater as time increases until the 5% limit is reached. Since the need for a minimum error occurs at a definite time interval after zero, the second method is preferable because one can draw a straight line to obtain zero error at any desired time. Another advantage of this method is that either a smaller RC time constant can be used with a given error, or a smaller error limit can be realized with a given RC time.

The R_2C_2 product was determined by mathmatically comparing the output voltage curve with its tangent through the origin, and then modified when the output voltage curve was compared to a straight line drawn for equal areas of error.

Comparison to the tangent:

$$e_o = f(1 - \epsilon^{-x}) \qquad \text{where } x = \frac{t}{R_2C_2}$$

$$(1-\epsilon^{-x}) = x - \frac{x^2}{2} + \frac{x^3}{6} - \frac{x^4}{24} + \text{------}$$

$$\text{tangent to the exponential} = \frac{t}{R_2C_2} = x$$

Desire the tangent to equal the exponential within 5%.

$$x = x - \frac{x^2}{2} + \frac{x^3}{6} - \frac{x^4}{24} \qquad \text{(within 5\% at end of 5 seconds)}$$

For terminated alternating series, the error is less than the first term dropped.

Therefore $$\frac{x^2}{2} = .05x$$

$$x = .1 = \frac{t}{R_2C_2}$$

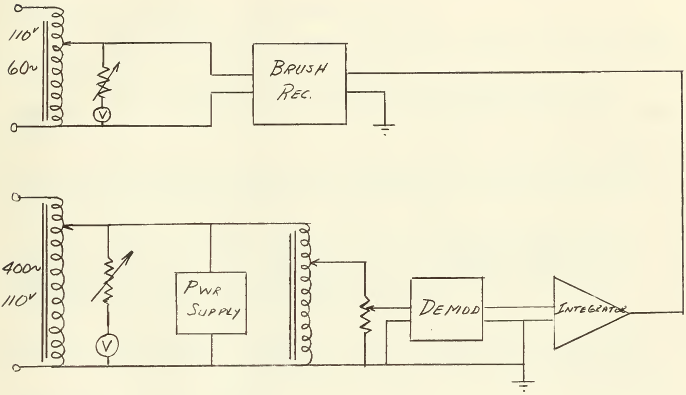
$$R_2 = 50M$$

This high resistance was not desirable because the moisture and dust encountered under typical operating conditions form a conductive layer on the surface which tends to lower such a high resistance.

A value approximately half that large could be obtained by drawing a line through the output curve to obtain equal areas of error. (See appendix, fig. 2).

It was decided, therefore, to run tests with various values of R_2 to determine its value. Calculations showed that a seventy volt output was obtained using the tentatively chosen values. This was considered satisfactory; determining the final value of R_2 and verifying all the calculations, were the remaining items to be accomplished.

Because of the tremendous variations in line voltages, the following measuring circuit was set up.



Although the Brush recorder and power supply have regulated plate supply voltages, the filament voltages are not regulated. The Brush recorders were calibrated, because at large amplitudes a definite non-linearity existed. The calibration consisted merely of feeding various known d-c voltages into the recorder and measuring the deflection. The known voltages were obtained by measuring the voltage across a "B" battery with a very accurate voltmeter, and then connecting a duodial heliopot across the battery to vary the voltage.

When the integrating amplifier is in actual operation,[4] its input is grounded, and the terminals of the integrating capacitor are shorted so that no initial zero signal error exists. This was accomplished by a DPDT switch in order to apply the input voltage

Note: [4] Functional Diagram of X5A Computer

at the same time the short is removed from the capacitor.

In the computer, the demodulator feeds the input signal into the integrator; for the tests*, the same procedure was used in order to simulate operating conditions.

The first series of tests was designed to discover how satisfactory the tentative values would be, and consisted of measuring the output curves with different input step voltages.

SUMMARIZING THE RESULTS: (See appendix, fig. 3)

For a step input of 44 volts, the output voltage was 69 volts after 5 seconds, which was considered satisfactory.

Using a straight line drawn through the origin and the 3.4 seconds point, the linearity was excellent; the maximum error was less than 2.5%.

The linearity of the curves did not depend on the input voltage. The family of curves for various input voltages (5 to 44 volts) showed no change in linearity with a change in input voltage.

The plotted curves coincided with the calculated curves within measuring limits. The next series of tests was designed to show the effect of any change in the components of the R-C network. Keeping the input voltage and two of three network components constant, the output voltages were measured with the following results:

Increasing R_2C_2 flattened out the exponential curve causing it to approach its tangent through the origin. (theoretical linear curve).

R_2 was not critical; it did not affect the gain nor the linearity (when R_2C_2 was high enough).

C_2 was critical; it affected the gain and the linearity (if R_2C_2 was not high enough).

R_1 was critical; it affected the gain, but not the linearity.

On the basis of the results, the values of R_1 and C_2 were fixed at 3 Megohm and 1 mfd respectively.

To determine R_2, curves were run to determine its effect on zero signal output as well as linearity. For R_2 = 30 Megohm, the linearity error was about 2% with a zero signal output of 26 millivolts. For values less than 30 Megohm, the linearity became too poor, while for values above that, the linearity improved, but the zero signal output became too high.

* In the final tests for voltage variations and excessive temperature conditions, the demodulator was not used.

Considering the additional factors of increased leakage with increasing resistance previously mentioned, and the inability to predict the effect of age on the carbon resistor, the best compromise among all the factors concerned was to choose a 30 Megohm carbon resistor of 5% tolerance.

With the network values definitely decided upon, the integrator was tested for linearity and zero signal output under varying filament and plate supply voltages, different tubes, and varying ambient conditions. There were no measurable changes, showing that the integrator is independent of:

1. input voltages to at least 50 volts.
2. ± 10% change in plate supply and filament voltages.
3. difference in tubes and / or changes in tube characteristics to about ± 25% change in mutual conductance.
4. operating temperatures up to at least 90° C.

To check the validity of the results even further, the transient response of the system was calculated in addition to plotting the log modulus vs phase angle curve.

Determining the Transient Response :

Since $^{3}KG = \left[1 + \frac{70}{(1+.02s)(1+6s)}\right]\left(\frac{3500}{1+.05s}\right)$

$$= 4.14 \cdot 10^{7} \; \frac{(s+31.2)(s+19)}{(s+200)(s+50)(s+1/6)}$$

Then : $\frac{E_o}{E_1} = -\frac{Y_1}{Y_2}\left[1 - \frac{Y_1+Y_2+Y_3}{KGY_2} + \left(\frac{Y_1+Y_2+Y_3}{KGY_2}\right)^2 + \ldots\ldots\right]$

$$0 < \frac{Y_1+Y_2+Y_3}{KGY_2} < 1$$

Where: $Y_1 = G_1 = .333$ Micromho

$Y_2 = G_2 + C_{2s} = .033$ Micromho $+ 10^{-6}s$

$Y_3 = G_3 = .5$ Micromho

$n = \frac{1}{R_2C_2}$

$e_1 = 42.3v$

Note: ^{3} AA4 Report: C.Glover

For a step input voltage $e_{in} = e_1 u(t)$

$$E_o = \frac{E_1}{R_1C_2}\ s(s+n)\left\{1-\left[\frac{s+\dfrac{G_1+G_2+G_3}{C_2}\qquad(s+200)(s+50)(s+1/6)}{(s+n)(s+31.2)(s+19).4.14.10^8}+\ldots\right]\right\}$$

Using theorem 19b from Gardner & Barnes to take the inverse, and substituting the values:

<u>At t = 5 seconds</u>

$$e_o = 440(1-\epsilon^{-.167}) - 3.4\cdot10^{-7}(388\epsilon^{-.1667} + .0027 + 1.21\epsilon^{-95} + 93.5\epsilon^{-166})$$

$e_o = 68$ volts

<u>At t = 0</u>

$e_o = -55$ Microvolts

The transient response of the system definitely shows that the first order approximation of $\frac{Y_1}{Y_2}$ is more than accurate enough for the purpose in hand. Any second order effects introduced by the amplifier are negligible and can be ignored with no loss in accuracy. Notice that there are no transient oscillations and the initial voltage is in the microvolt range.

Log Modulus vs Phase Angle Plot

The purpose of this plot is to graphically change:

$$KG\frac{Y_2}{Y_1+Y_2+Y_3} \quad \text{to} \quad \frac{KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}{1+KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}$$

Treating the integrator as a servo system:

$$\frac{e_o}{e_i} = \frac{KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}{1+KG\dfrac{Y_2}{Y_1+Y_2+Y_3}}$$

From a plot of this equation, the frequency response of the integrator in terms of db gain and phase shift, as well as its stability may be seen at a glance.

$$^{2}KG = 4.14 \cdot 10^{7} \frac{(s+31.2)(s+19)}{(s+200)(s+50)(s+ 1/6)}$$

$$\frac{Y_2}{Y_1+Y_2+Y_3} = \frac{s + .033}{s + .866}$$

Let M = absolute value of $KG \dfrac{Y_2}{Y_1+Y_2+Y_3}$

N = phase angle of $KG \dfrac{Y_2}{Y_1+Y_2+Y_3}$

Replacing s by $j\omega$, and tabulating the results:

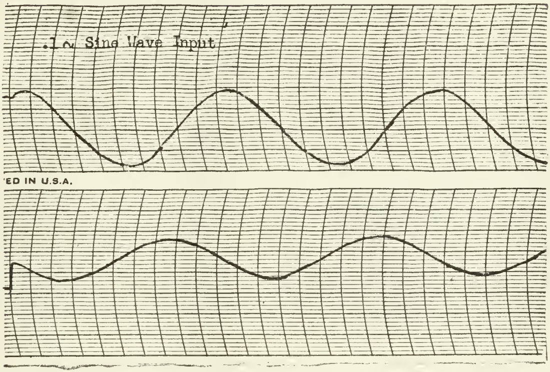
ω	M(db)	N(degrees)	$\frac{MN}{1+MN}$	
0	143.2	0°	essentially 0 db at 0° phase shift	
20,000	66.4	-90°	essentially 0 db with less than 2° phase shift	
$1.04 \cdot 10^{6}$	+32	-90°	0 db	-2°
$4.14 \cdot 10^{7}$	0	-90°	-3 db	-88°
$16.5 \cdot 10^{8}$	-30	-90°	-28 db	-88°

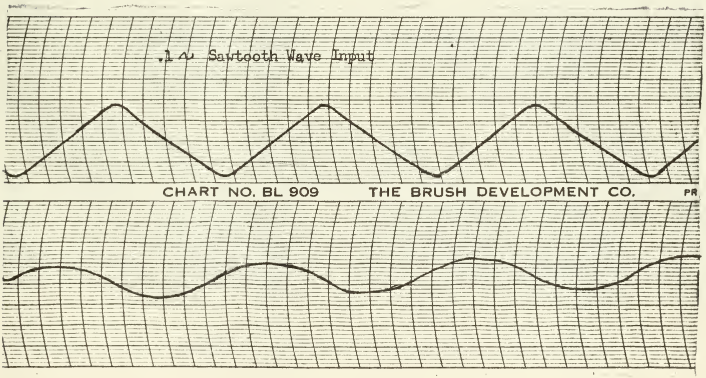
If these results were plotted on a log modulus vs phase angle chart[5], the resulting curve would be a vertical straight line along the -90° phase shift line from ω = 20,000 (+66.4db) to ω approaching infinity. The phase margin is 90°.

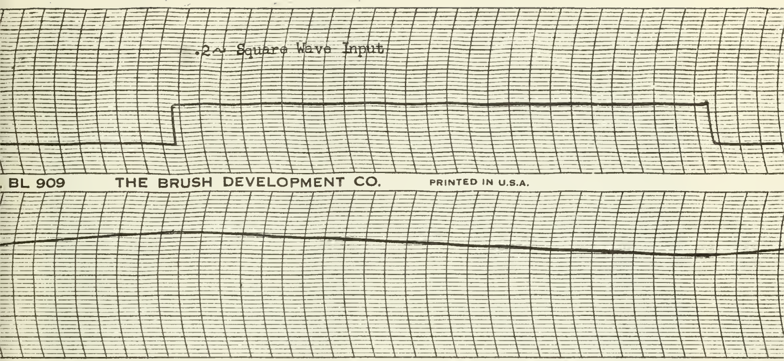
Note: [5] Fig. 11.5-2, p 351, Servomechanisms and Regulating Systems, Vol. 1: Chestnut and Mayer

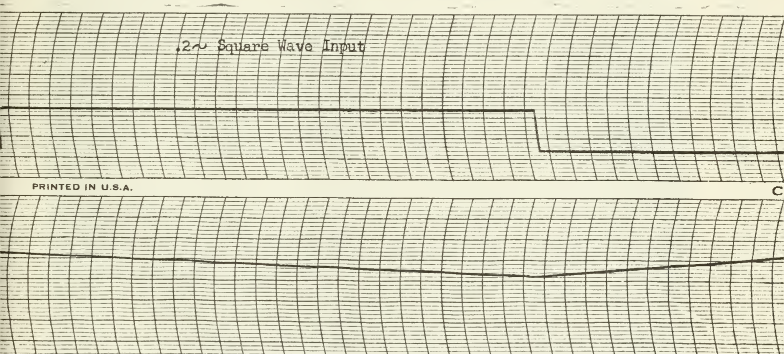
/en

Low frequency sine, triangular, and square waves were fed into the integrator. The integrator behaved as expected (see below).






.2~ Square Wave Input
BL 909 THE BRUSH DEVELOPMENT CO. PRINTED IN U.S.A.


.2~ Square Wave Input
PRINTED IN U.S.A.

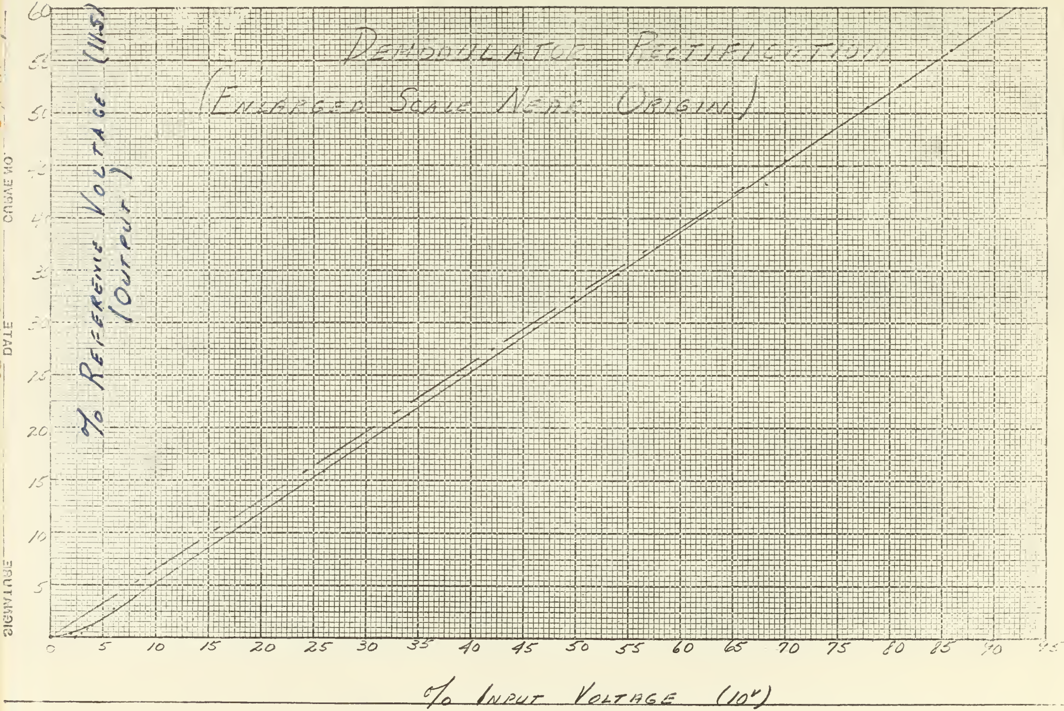
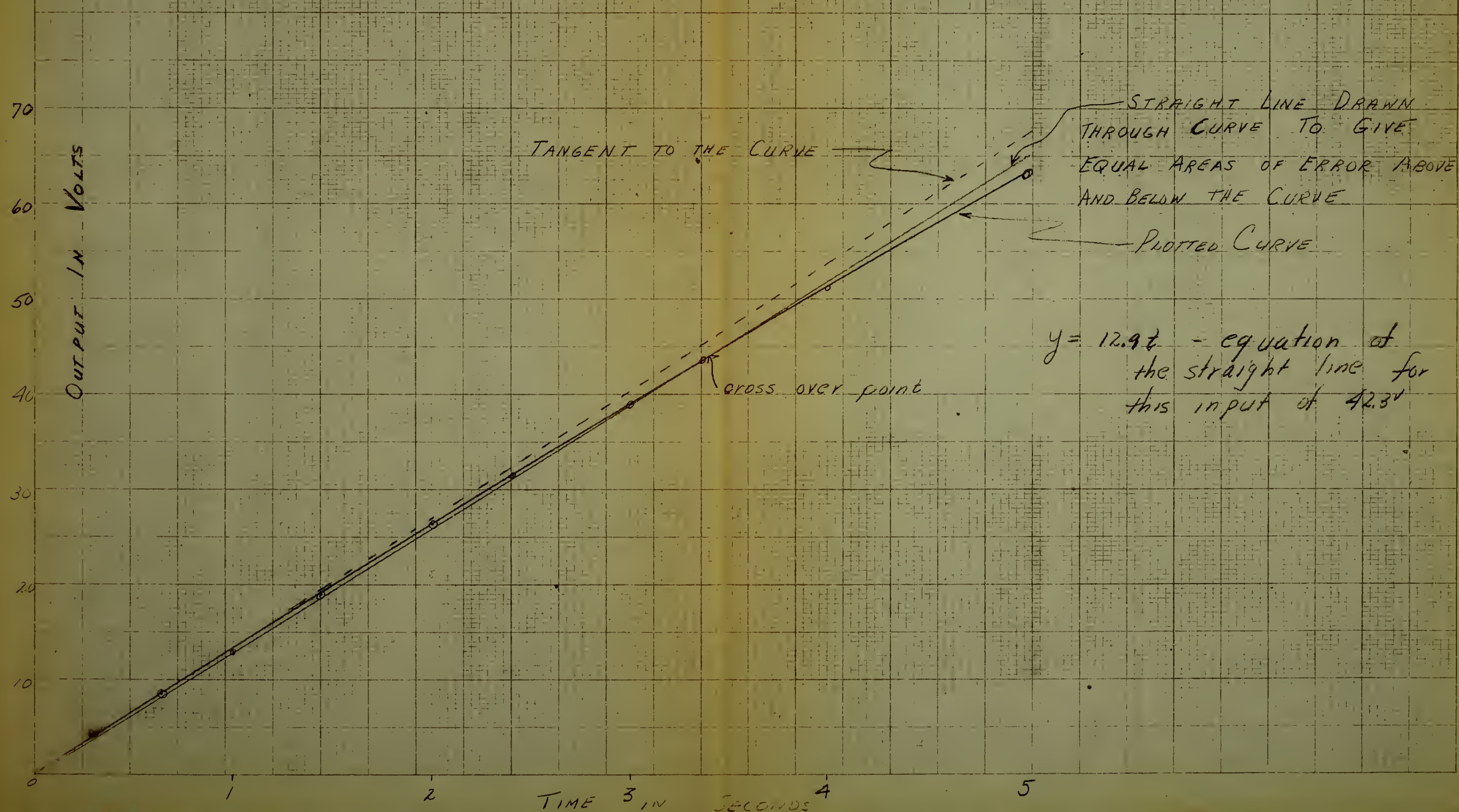

DEMODULATOR RECTIFICATION
(ENLARGED SCALE NEAR ORIGIN)
% REFERENCE VOLTAGE (115) (OUTPUT)
% INPUT VOLTAGE (10V)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95
5 10 15 20 25 30 35 40 45 50 55 60

FIG 2

Approximating The Exponential Output Curve by a Straight Line



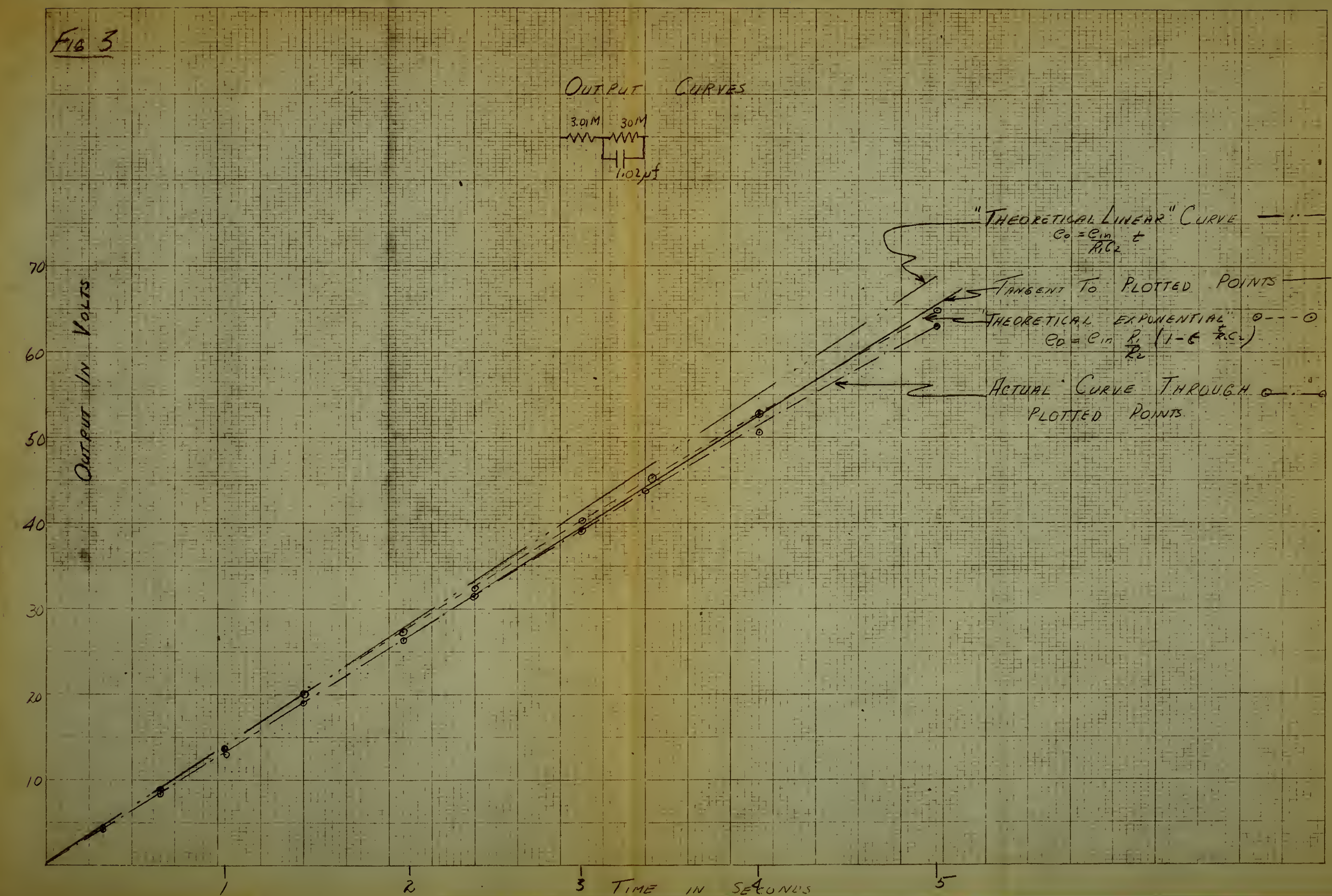
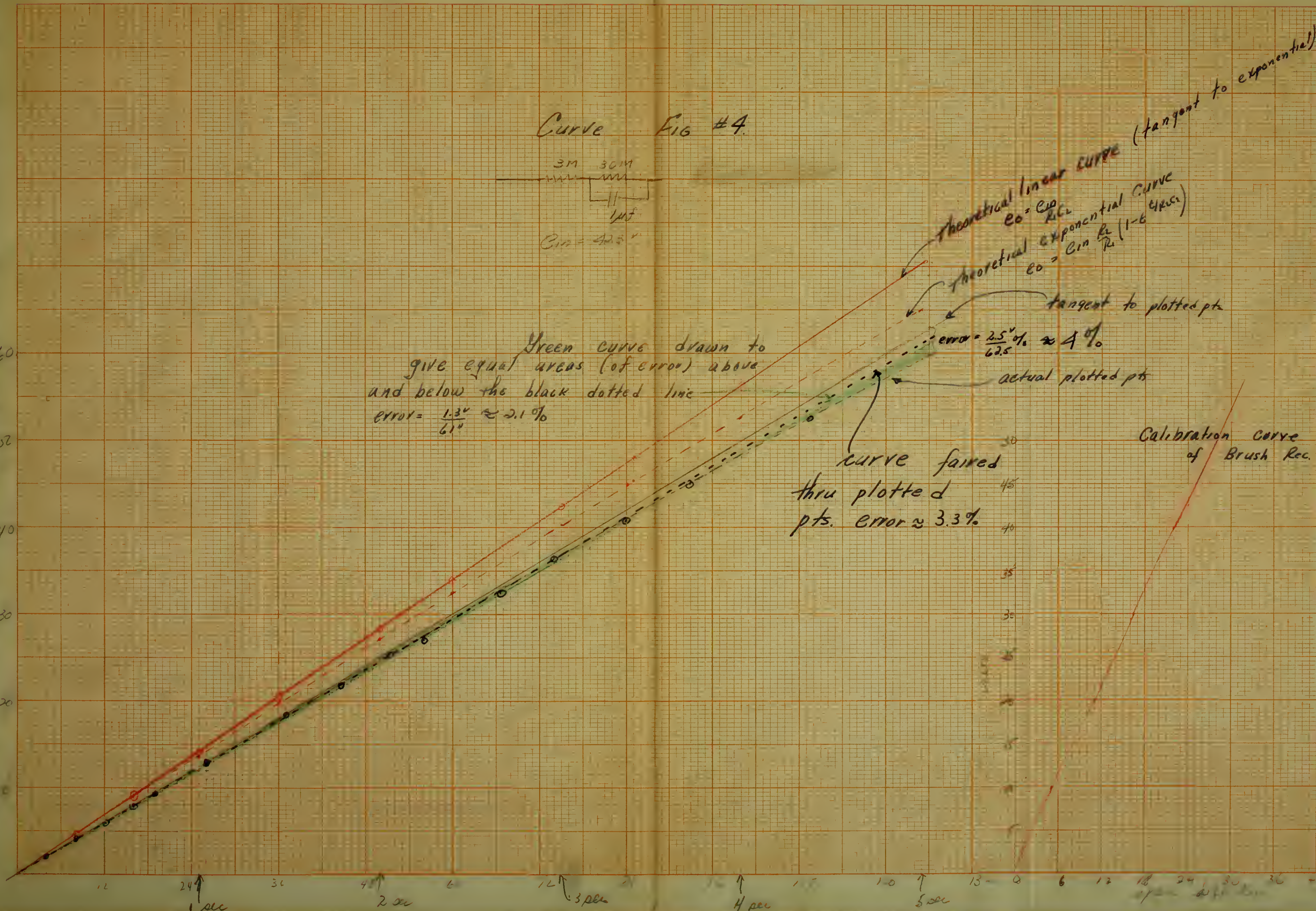
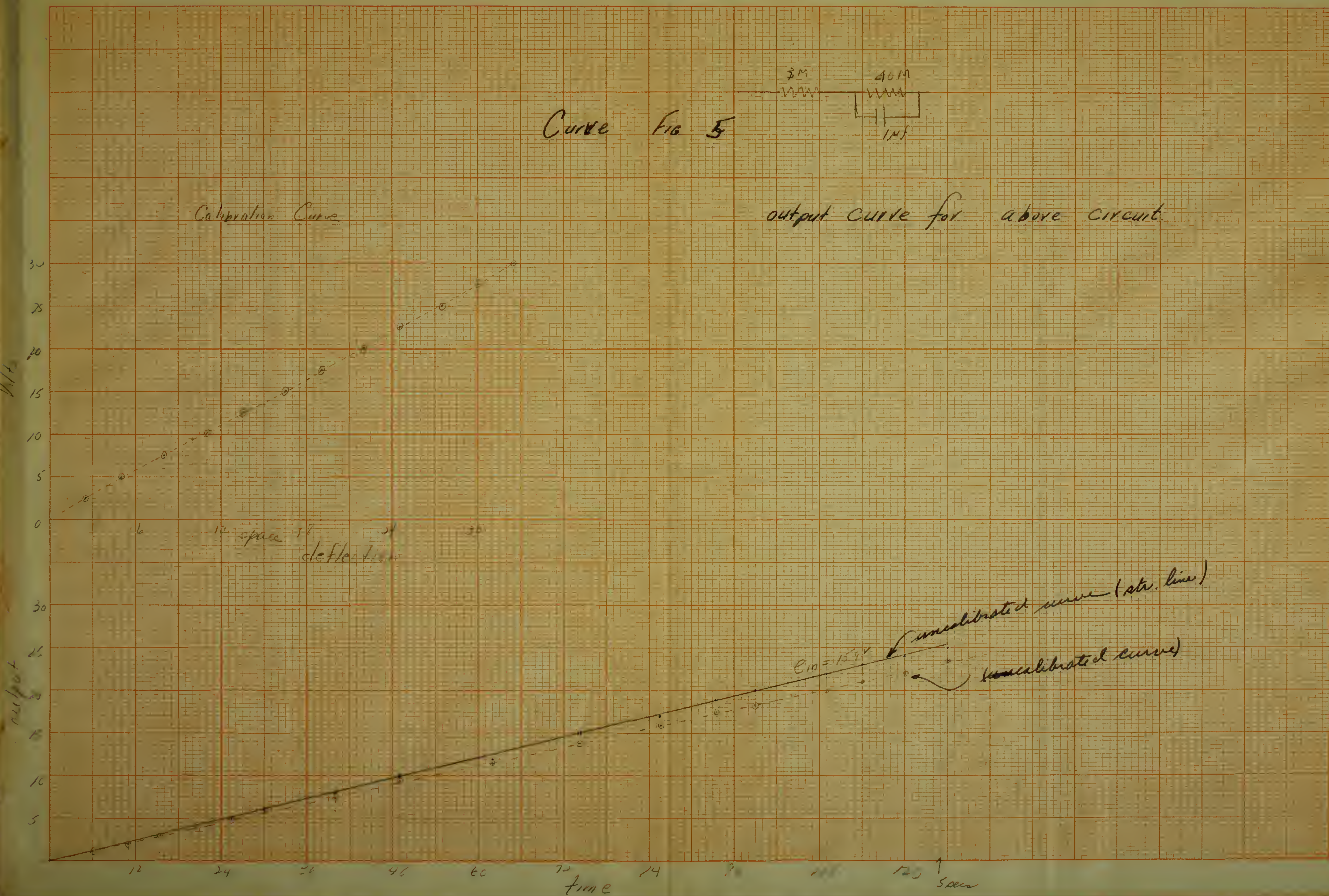
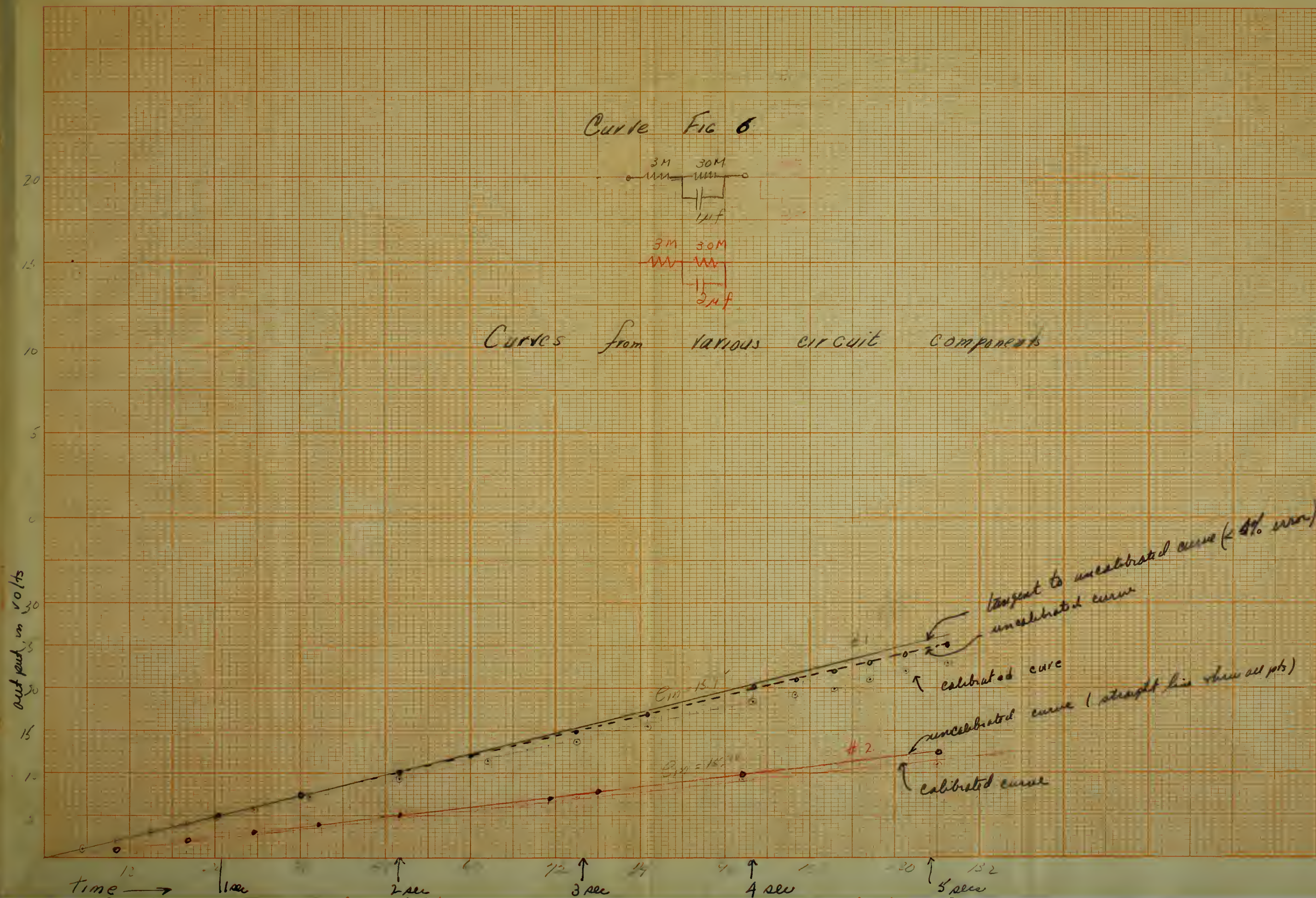


Fig 3
Output Curves
3.01M
30M
1.02μf
"Theoretical Linear" Curve
$e_o = \frac{e_{in}}{R_1C_2} t$
Tangent To Plotted Points
"Theoretical Exponential"
$e_o = e_{in} \frac{R_1}{R_2} (1 - \epsilon^{-\frac{t}{R_2C_2}})$
Actual Curve Through Plotted Points
Output In Volts
Time in Seconds
10
20
30
40
50
60
70
1
2
3
4
5


Curve Fig #4
3M
30M
1µf
theoretical linear curve (tangent to exponential)
theoretical exponential curve
tangent to plotted pts
error = 2.5v/62.5 % ≈ 4%
actual plotted pts
Green curve drawn to give equal areas (of error) above and below the black dotted line
error = 1.3v/61v ≈ 2.1%
curve faired thru plotted pts. error ≈ 3.3%
Calibration curve of Brush Rec.
60
40
30
1 sec
2 sec
3 sec
4 sec
5 sec

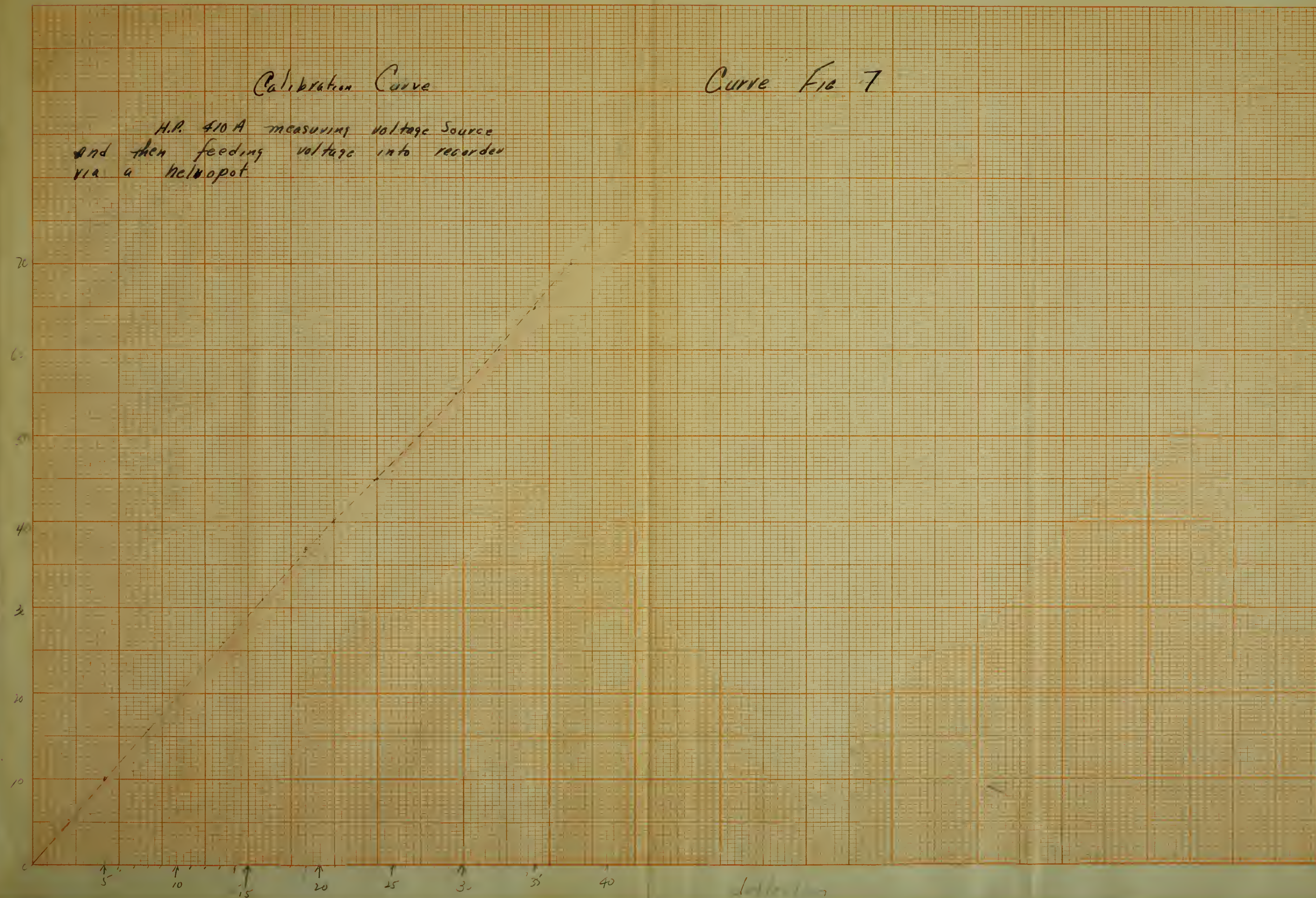

Curve Fig 5
3M
40M
1μf
Calibration Curve
output curve for above circuit
volts
space deflection
uncalibrated curve (str. line)
$e_{in} = 15.9^V$
uncalibrated curve
output
time
secs

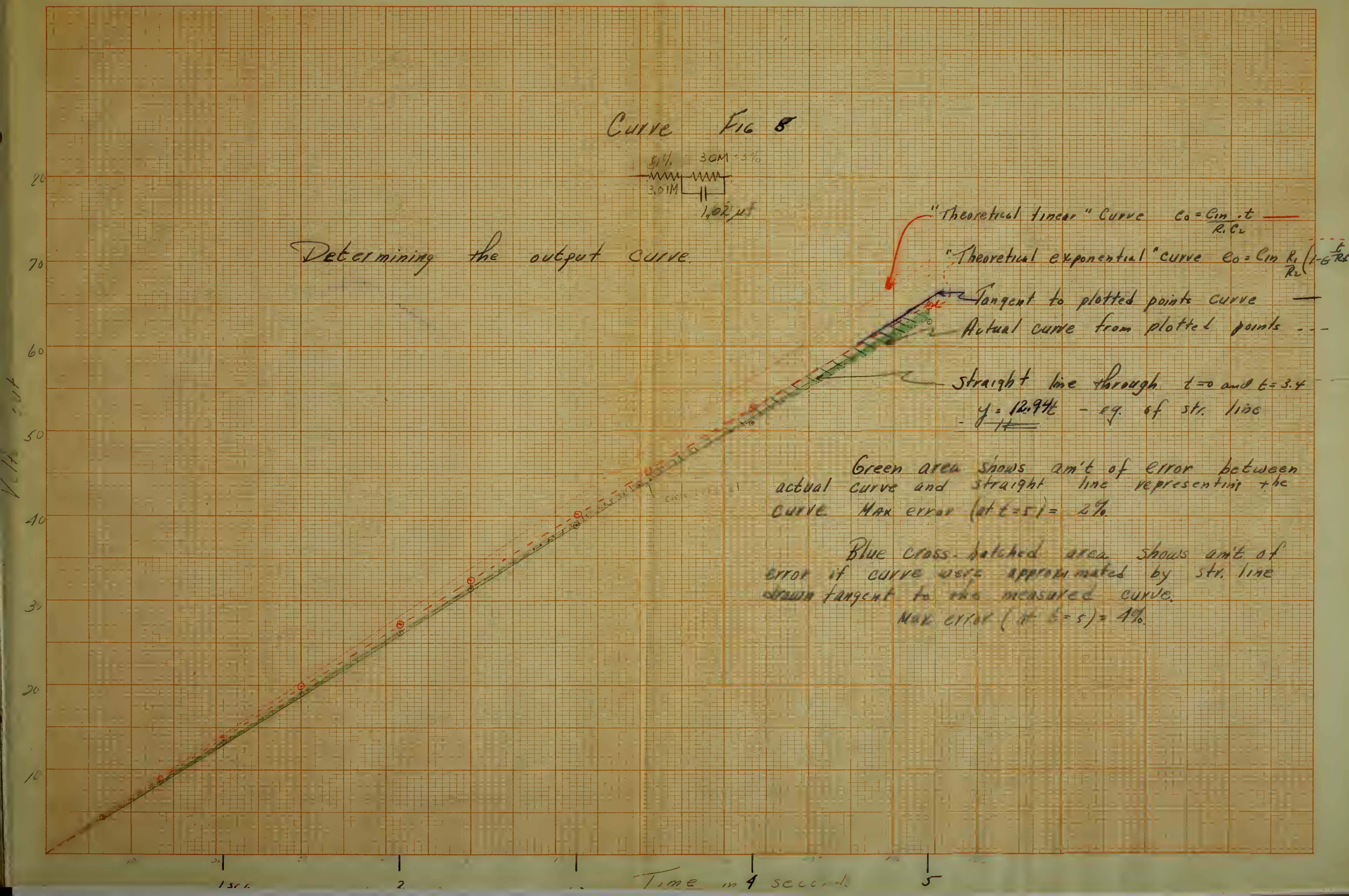


Curve Fig 6
3M
30M
1μf
3M
30M
2μf
Curves from various circuit components
tangent to uncalibrated curve (< 4% error)
uncalibrated curve
#1
calibrated cure
uncalibrated curve (straight line thru all pts)
#2
calibrated curve
output in volts
time →
1 sec
2 sec
3 sec
4 sec
5 sec

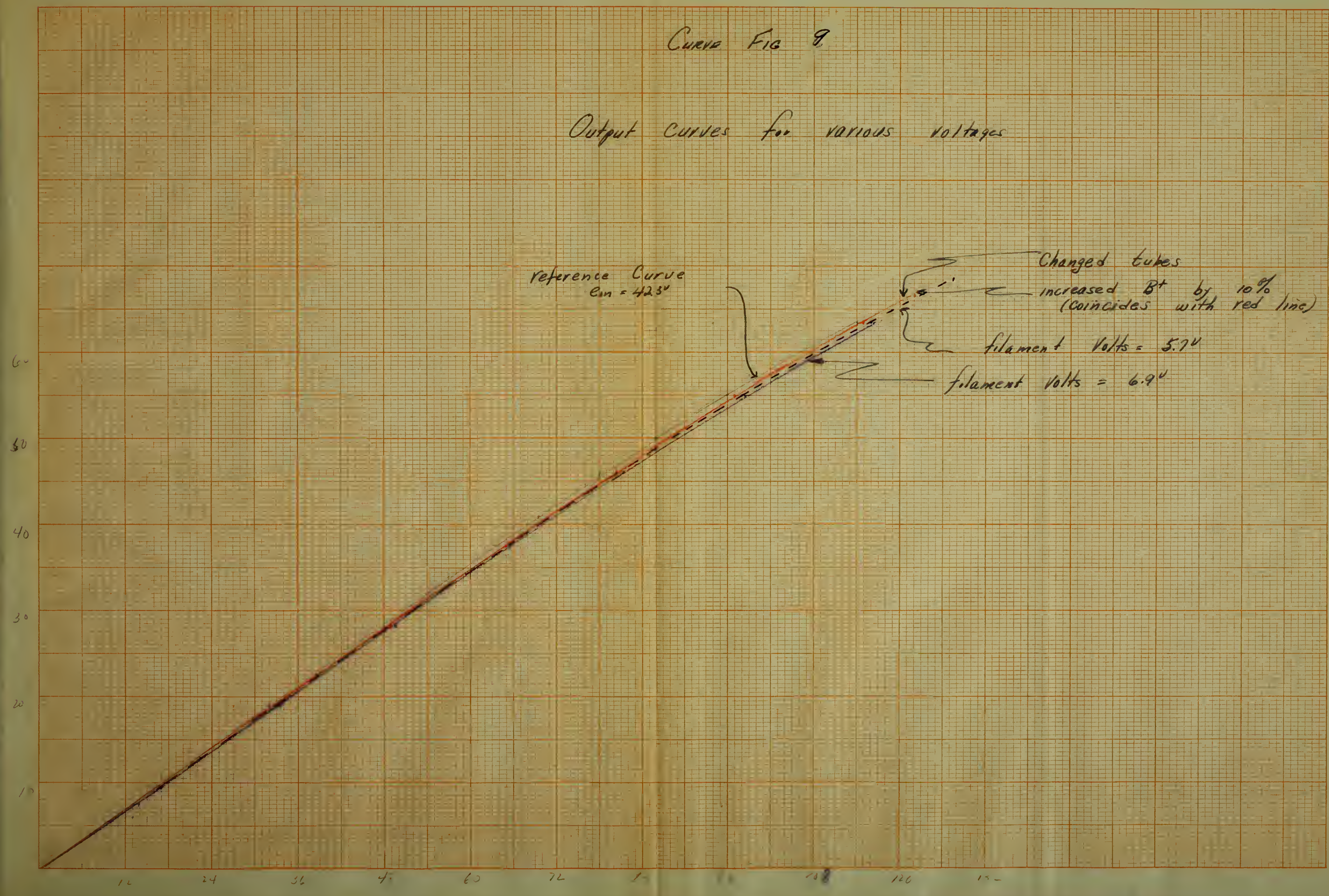
Calibration Curve

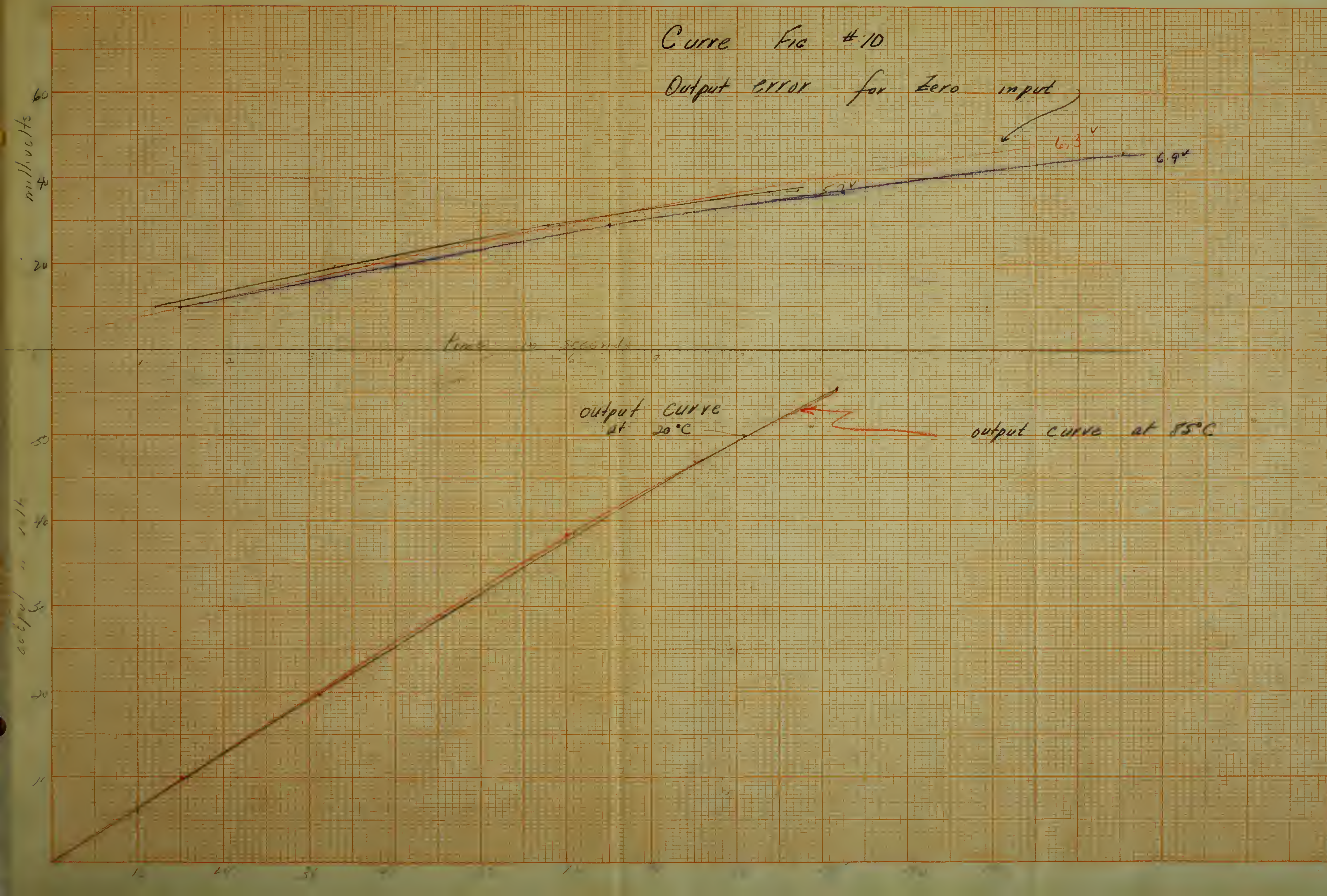
Curve Fig 7

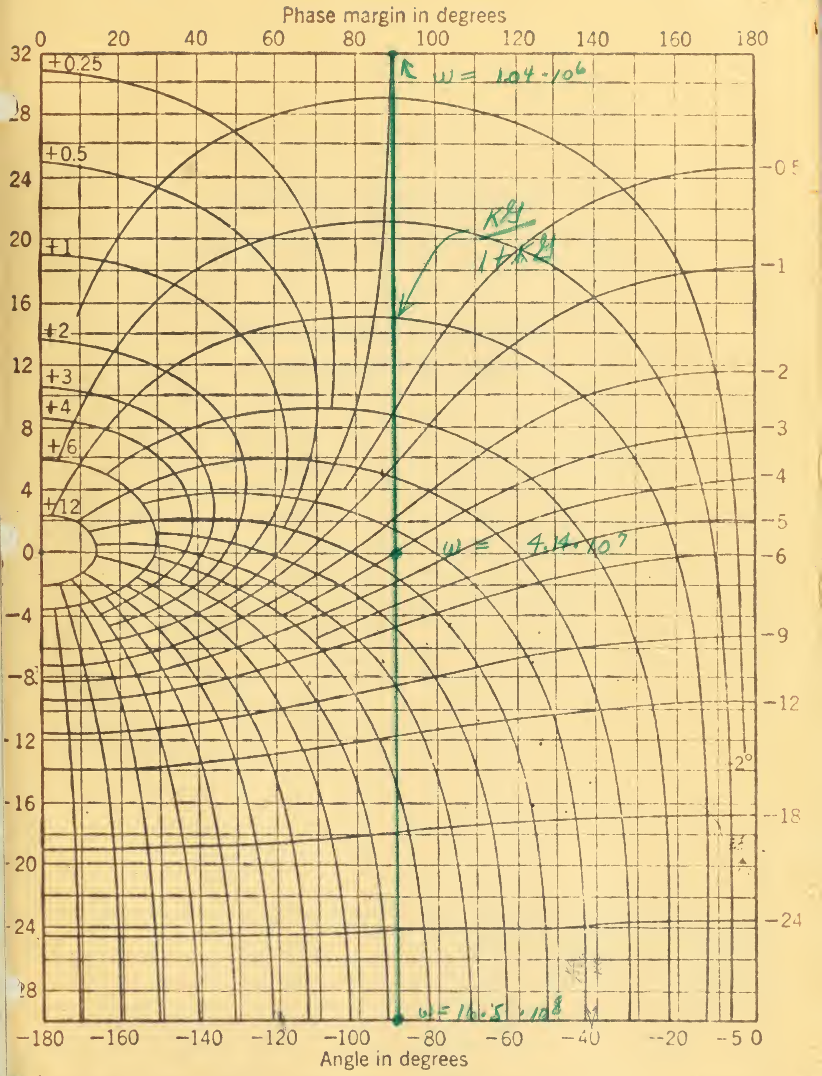




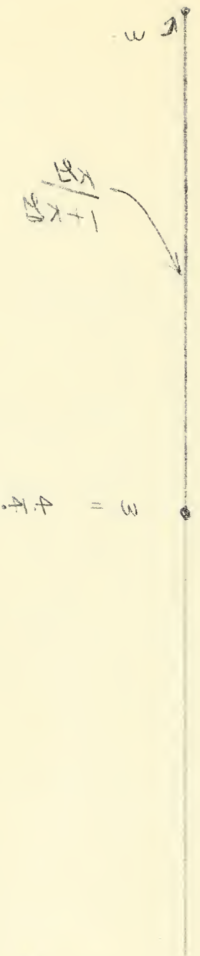
Curve Fig 8
3.01M
3.0M
1.02 μf
Determining the output curve.
"Theoretical linear" Curve $e_o = \frac{e_{in}}{R_1 C_2} \cdot t$
"Theoretical exponential" curve $e_o = e_{in} \frac{R_1}{R_2}\left(1 - e^{-\frac{t}{R_2 C_2}}\right)$
Tangent to plotted points curve
Actual curve from plotted points
Straight line through t=0 and t=3.4
y = 12.94t - eq. of str. line
Green area shows am't of error between actual curve and straight line representing the curve. Max error (at t=5) = 2%.
Blue cross-hatched area shows am't of error if curve were approximated by str. line drawn tangent to the measured curve.
Max error (at t=5) = 4%
Volts out
70
60
50
40
30
20
10
1 sec.
2
4
5
Time in seconds


Curve Fig 9
Output curves for various voltages
Reference Curve
e_{in} = 42.5v
Changed tubes
increased B+ by 10%
(coincides with red line)
filament Volts = 5.7v
filament Volts = 6.9v
10
20
30
40
60
12
24
72
108
120


Curve Fig #10
Output error for zero input
6.3v
6.9v
5.7v
millivolts
60
40
20
time in seconds
output curve at 20°C
output curve at 85°C



— Constant-phase-angle and constant-amplification contours on the decibel-ph
angle loop diagram



K ω
$\frac{KG}{1+KG}$
ω = 4.4·10^7
-1.2·10^8

NO. CDS67

DATE 3-19-52

WESTINGHOUSE ELECTRIC CORPORATION

AIR - ARM DIVISION

FRIENDSHIP INTERNATIONAL AIRPORT, BALTIMORE, MARYLAND

TEST OF TRANSFORMER TO BE USED IN THE

X5A BALLISTICS OUTPUT CIRCUIT

TEST OF TRANSFORMER TO BE USED IN THE X5A BALLISTICS OUTPUT CIRCUIT

SYNOPSIS:

Tests disclosed that the transformer had excessive phase shift which could not be corrected satisfactorily, and was, therefore, not acceptable.

STATEMENT OF PROBLEM:

Wheeling Insulated Wire Co. of Waterbury, Conn. supplied a transformer for the X5A ballistics output circuit. The transformer's phase shift and distortion characteristics were tested.

CONCLUSIONS:

A better transformer should be obtained.

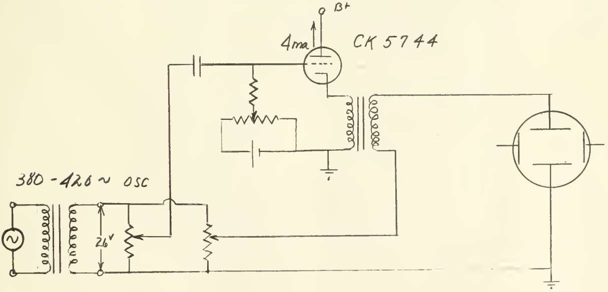
Although the distortion was negligible, the phase shift was excessive.

Corrective networks cannot be used because the capacitance value changes too much with frequency and the particular transformer used.

BODY OF REPORT:

The phase shift, itself, was not measured directly; it was determined, instead, as a function of the voltage which remained after a voltage applied across the transformer primary was "nulled" by a voltage of opposite phase applied in series with the secondary.

MEASURING CIRCUIT



The first heliopot feeds the reference voltage into the primary via the grid-cathode circuit, and the second heliopot feeds a voltage into the secondary which is opposite in phase to the voltage coupled over from the primary. With no phase shift nor distortion in the cathode and transformer, application of equal voltages would cause a null on the oscilloscope. Any distortion and phase shift would show as a voltage on the screen of the cathode ray tube, and this would be impossible to cancel out by varying the second heliopot. To be acceptable, this "null" voltage should be less than .5 volts peak to peak.

With an input voltage of 26 volts, measurements, taken at frequencies from 380 to 420 cycles, showed a minimum voltage of approximately 3.5 volts peak to peak. The undistorted cathode ray trace showed that this voltage was entirely due to phase shift. The use of Lissajous figures on the oscilloscope showed that the phase shift occurred almost entirely in the transformer.

Placing a shunt capacitor and resistor across the transformer secondary reduced the "null" voltage to about .8 volts peak to peak. Not only was this too high, but the capacitance was critical: it varied with frequency and the individual transformer under test.

The use of a blocking capacitor to remove the direct current component from the primary reduced the "null" voltage to an acceptable value, but the capacitance was still too critical, and therefore, unacceptable.

Thesis
B543 Biordi 28810
Integrating amplifier for
X5A computer.